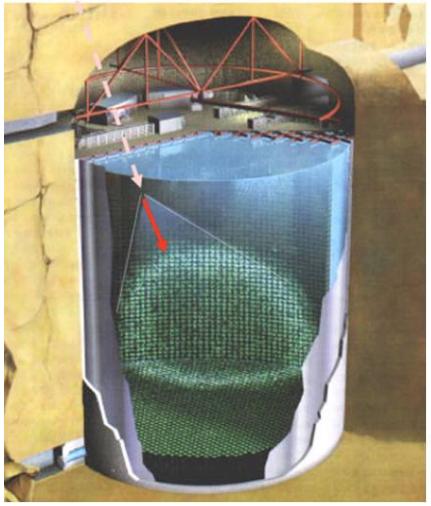
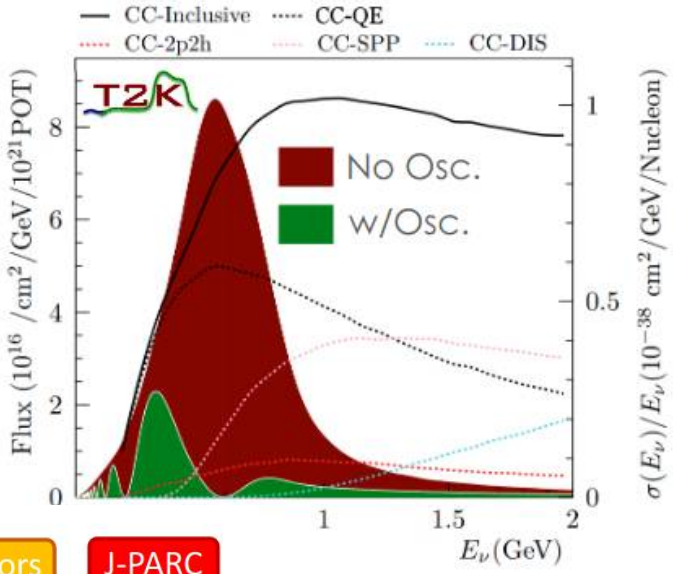
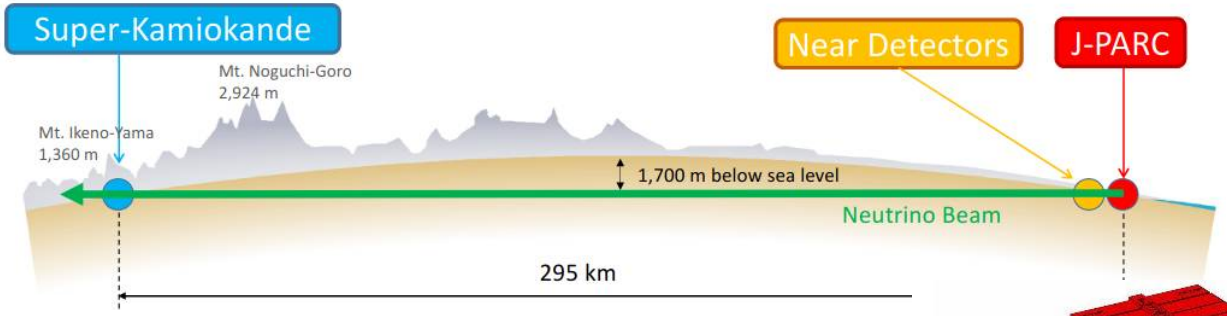
T2K Near Detector constraints for neutrino oscillation measurements

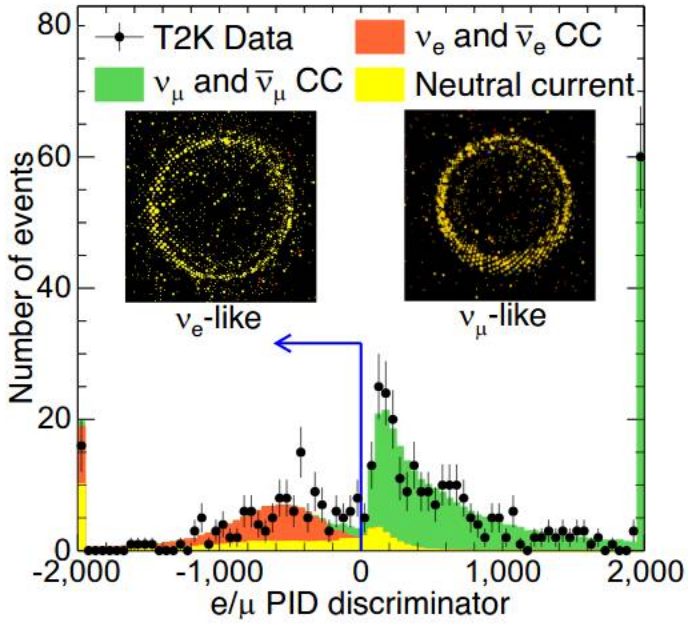
NuFact 2022
4th August 2022
Callum Wilkinson

BERKELEY LAB

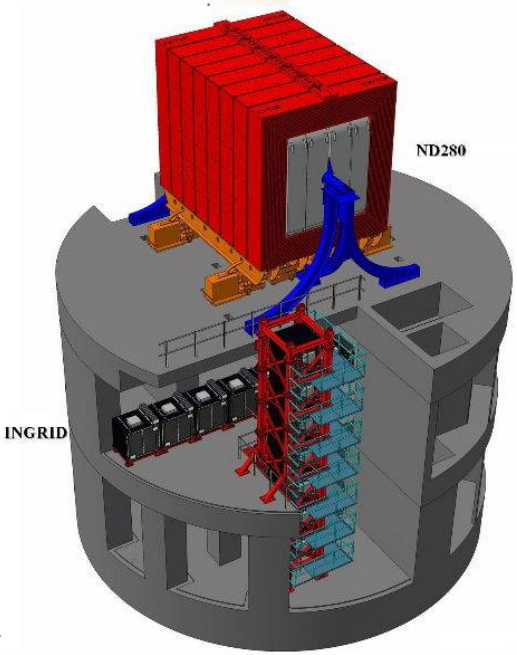






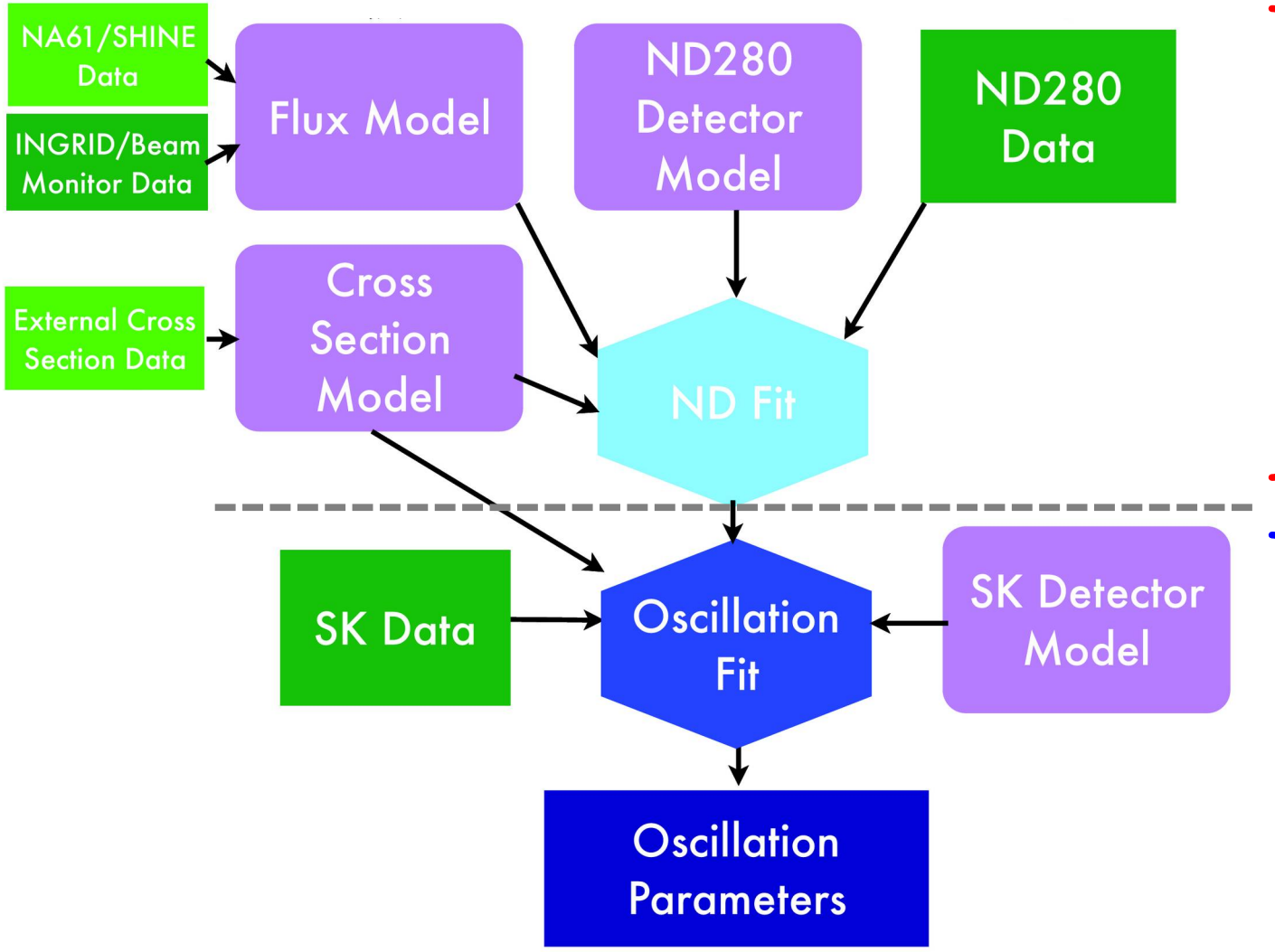


Nature 580, 339-344 (2020)



More details in
[L. Kormos's plenary talk]

T2K analysis in one slide



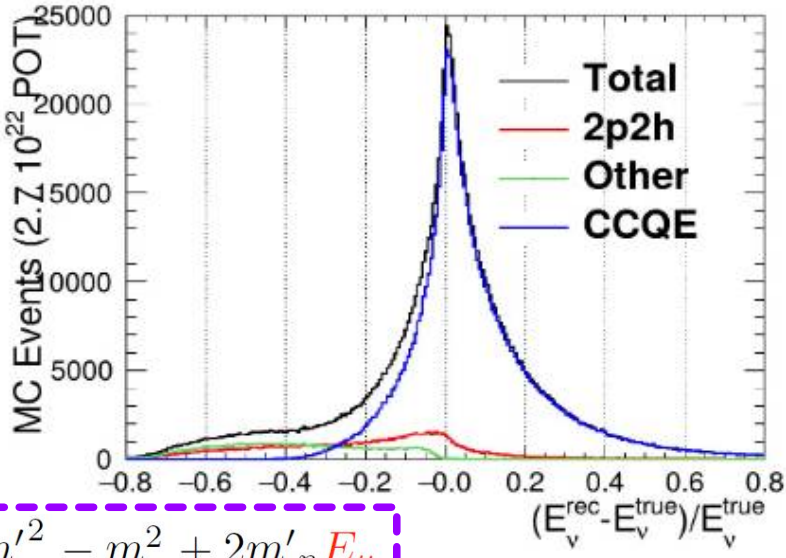
This talk

K. Yasutome's talk tomorrow!

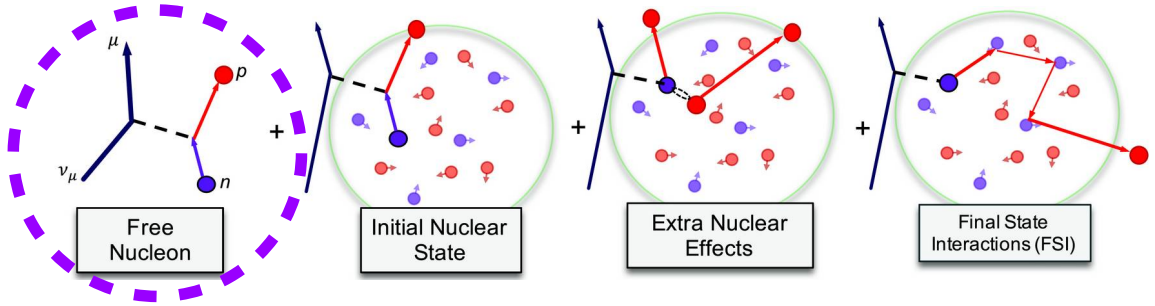
SK samples

- ν-mode 1R μ-like
- $\bar{\nu}$-mode 1R μ-like
- ν-mode 1R e-like
- $\bar{\nu}$-mode 1R e-like

CC0π

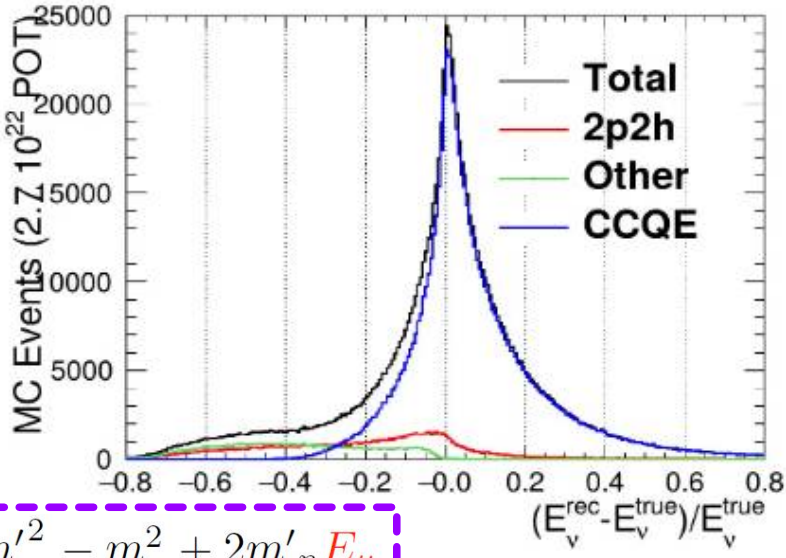


$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$



- ν-mode 1R e-like + 1 d.e.
- **New(!):** ν-mode ν_μ-CC1π^+

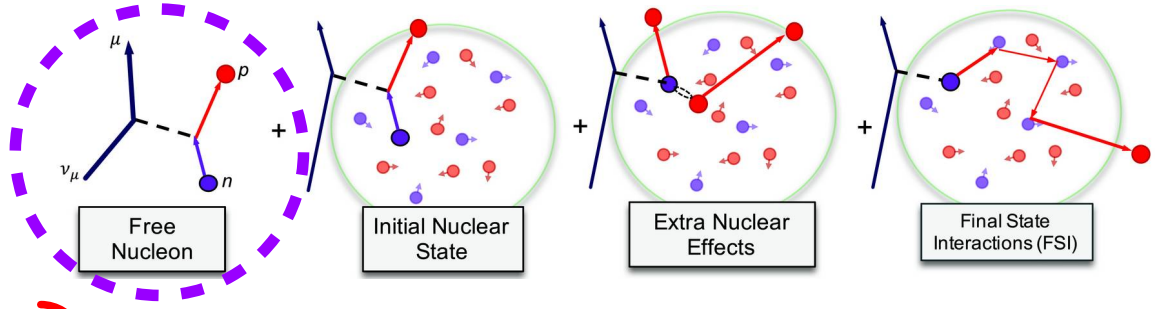
SK samples



- ν-mode 1R μ-like
- $\bar{\nu}$-mode 1R μ-like
- ν-mode 1R e-like
- $\bar{\nu}$-mode 1R e-like

CC0π

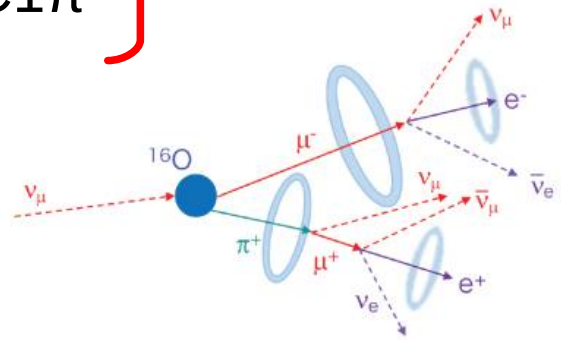
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$



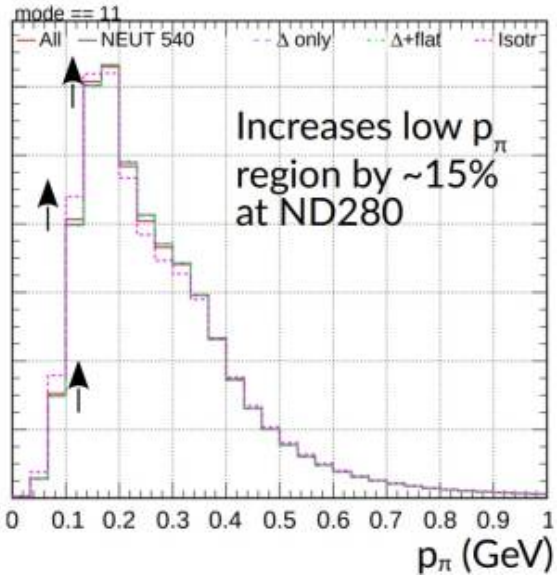
- ν-mode 1R e-like + 1 d.e.
- **New(!):** ν-mode ν_μ-CC1π^+

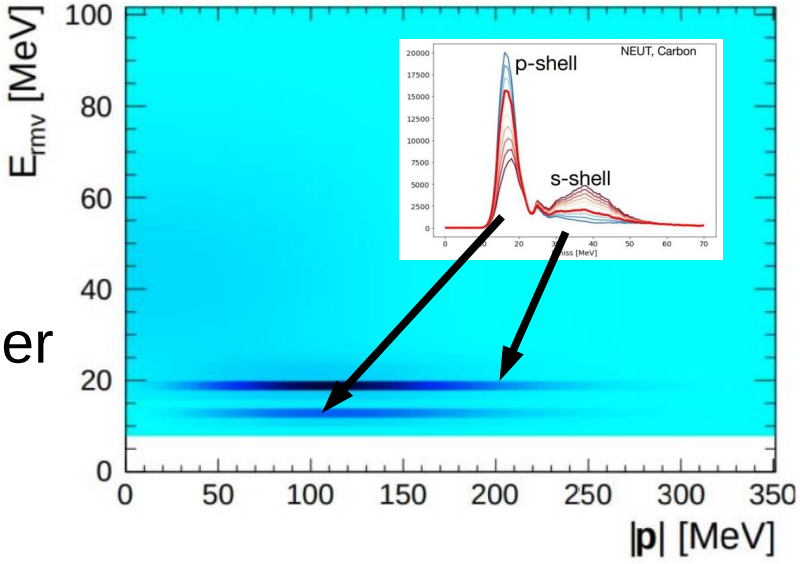
Single pion production

$$\nu_e + N \rightarrow e^- + \pi^+ + X$$
$$\downarrow$$
$$\mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$



Cross-section model

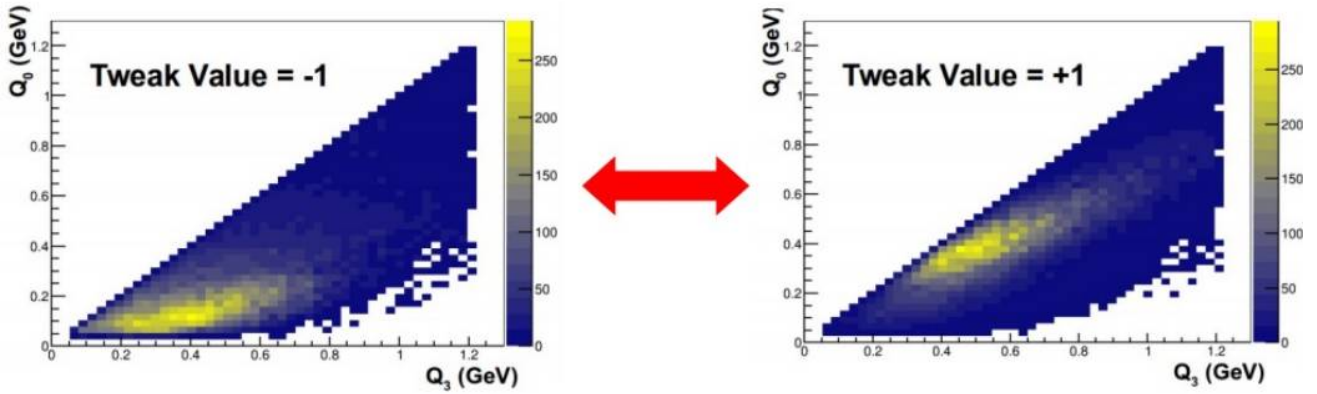




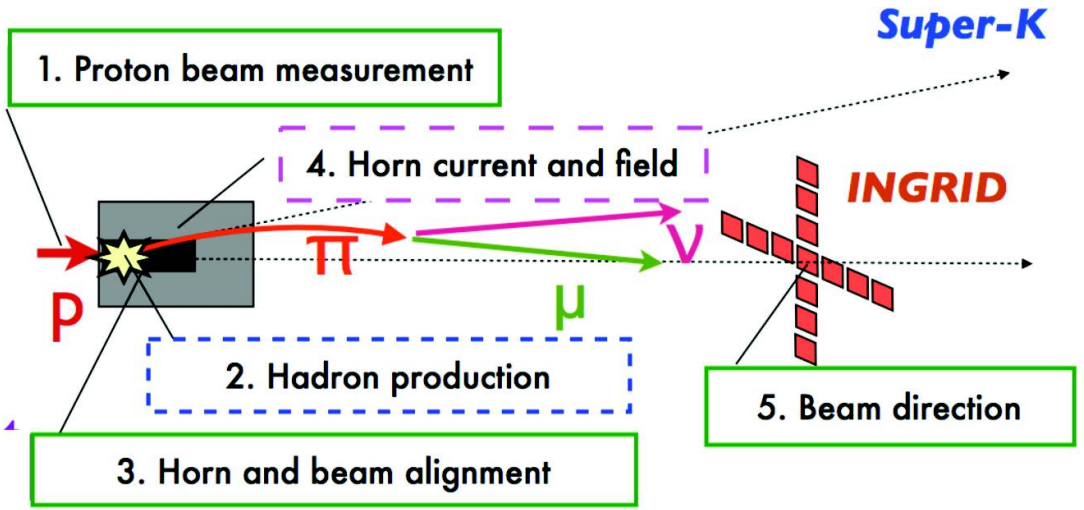
Developed along with other aspects of the analysis:

- E_ν and A-dependence
- Initial state nuclear model
- 2p2h and 1π contributions to CC0π
- Pion kinematics

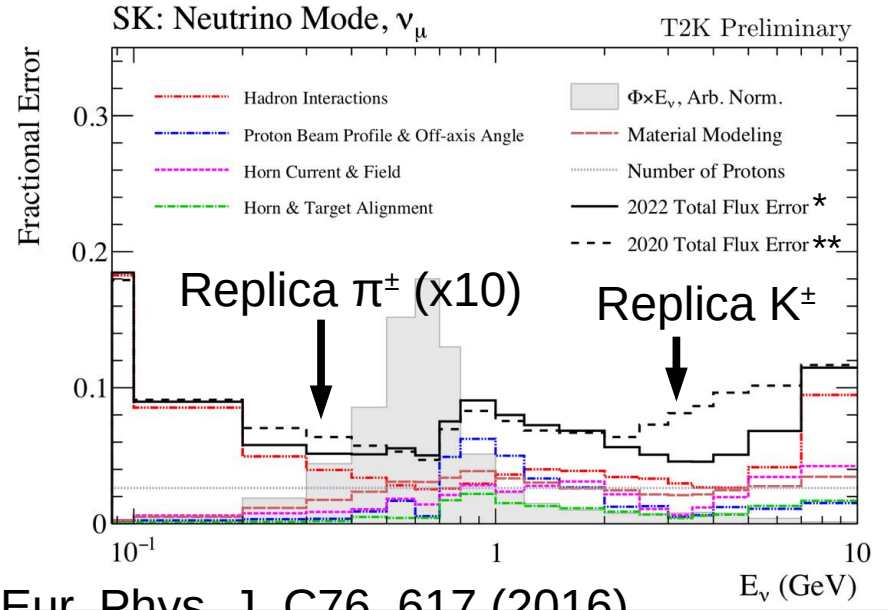
See [S. Dolan's talk] for details

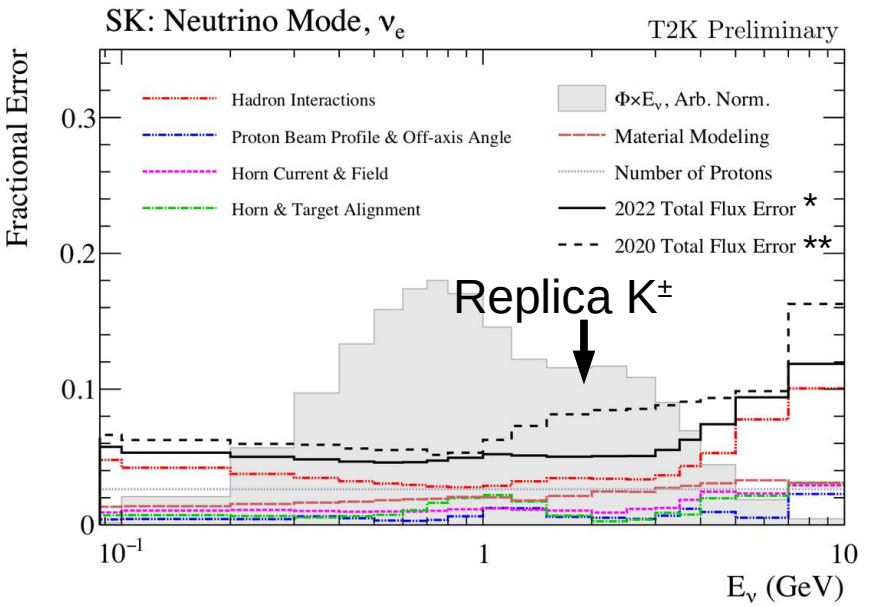


Neutrino beam



- Improved simulation with latest NA61 hadron multiplicity measurements
- Refined model for cooling water flow in horns

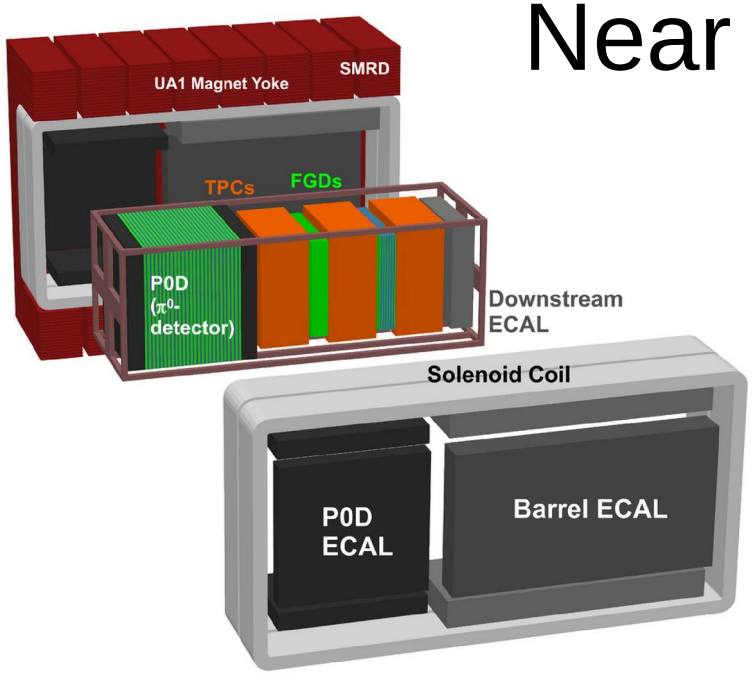




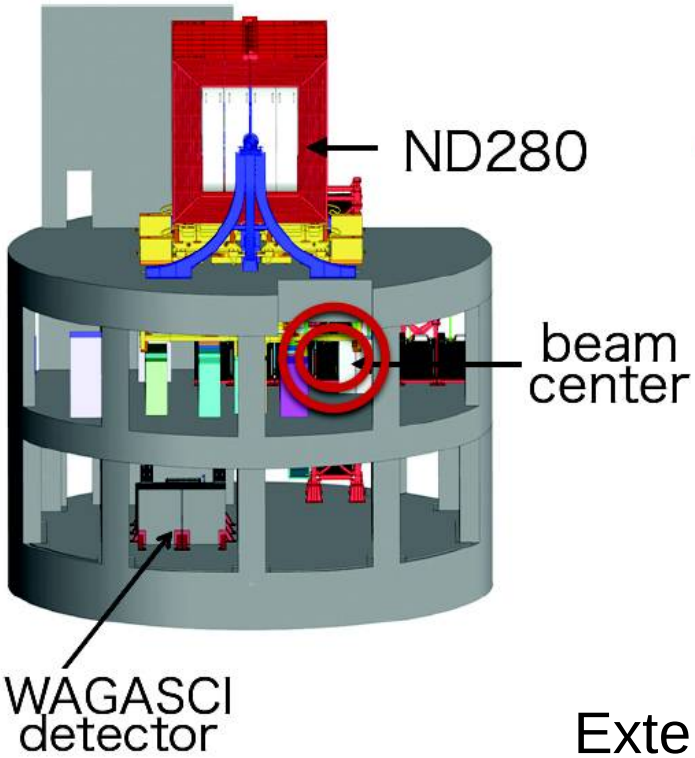
*Eur. Phys. J. C76, 617 (2016)

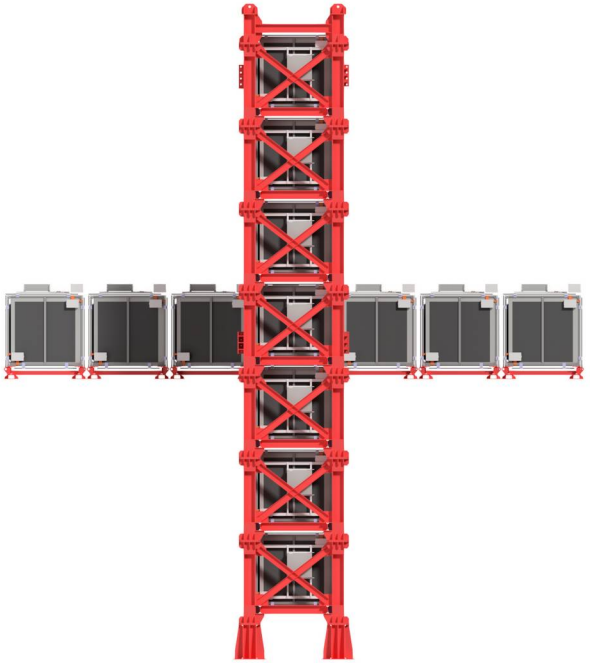
**Eur. Phys. J. C79, 100 (2019)

Near detector complex

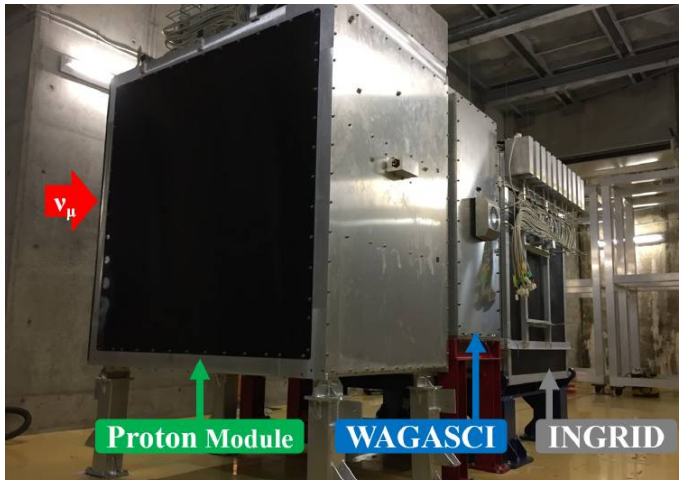


ND280 (2.5º)





INGRID (0º)

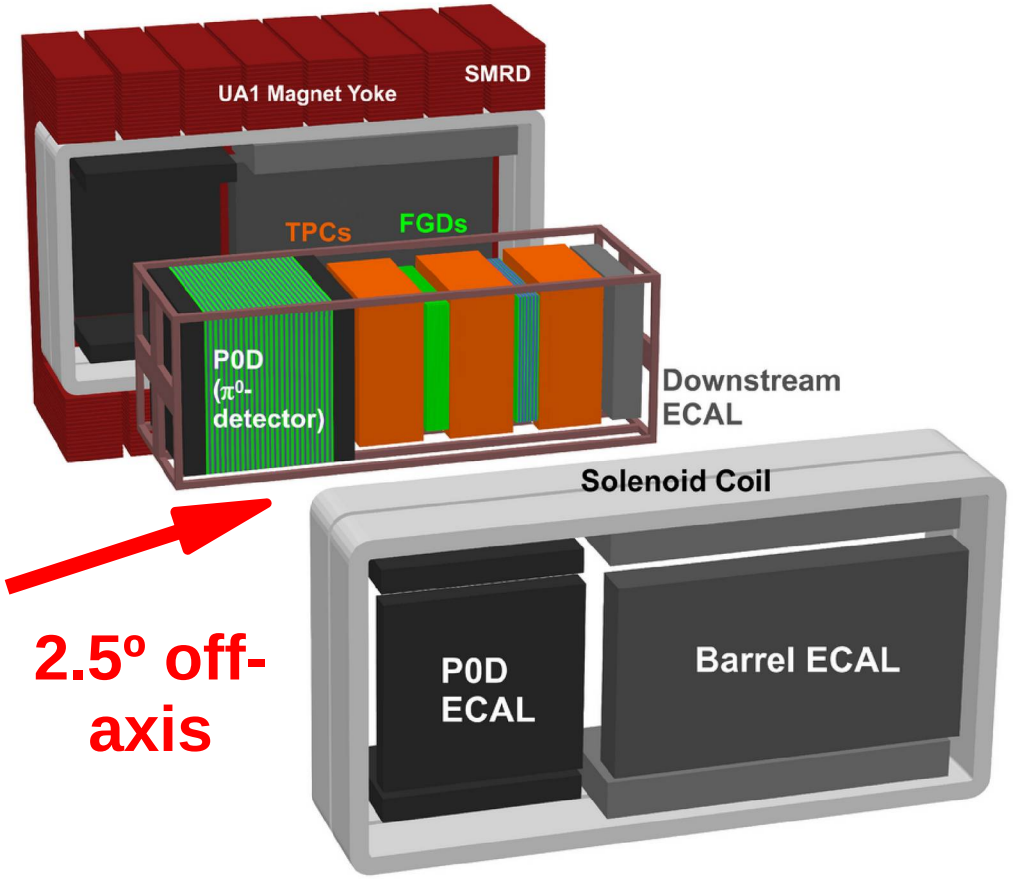


WAGASCI + BabyMIND (1.5º)

Extensive XSEC measurement program – see A. Cudd's talk for details

ND280 off-axis

- Same 2.5° off-axis angle as far detector
- 0.2 T magnet for sign and momentum determination



- **Fine grained detectors (FGDs):**
  - Scintillator and water targets
  - Interaction mass and tracking

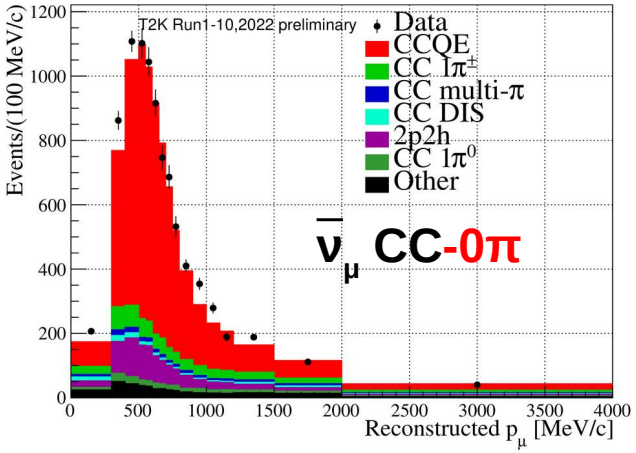
  Time Projection Chambers:
  - Gaseous argon
  - Momentum and dE/dx

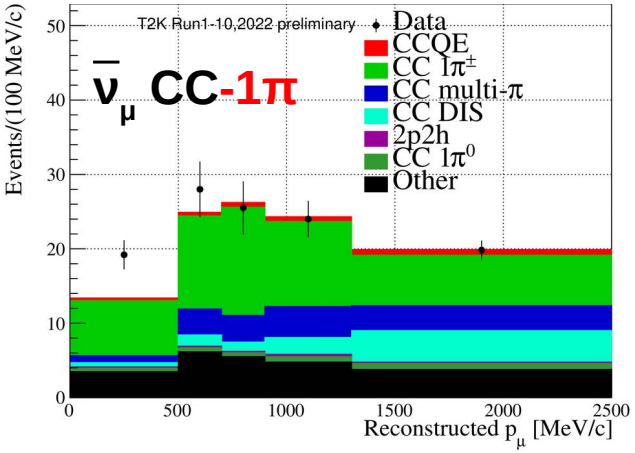
  ECals surrounding the above

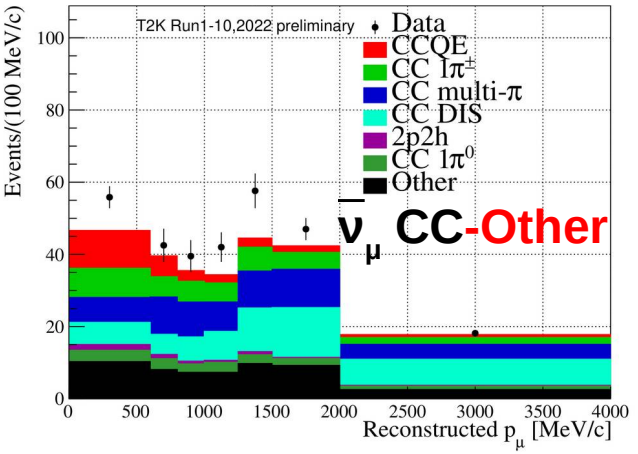
Previous: ND280 data

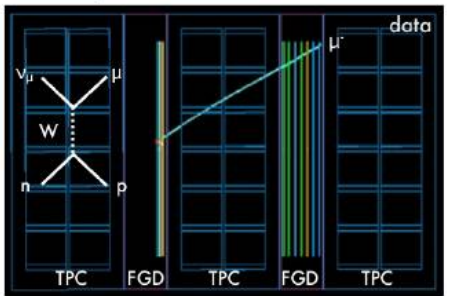
- Subdivide data based on number of final state pions
- ν and $\bar{\nu}$-modes (split into μ^+/μ^-)
- Samples on plastic (FGD1) and water/plastic mixed (FGD2) targets

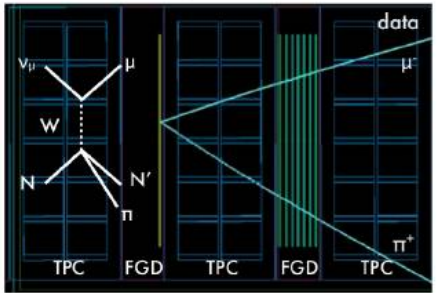
(FGD1 shown here)

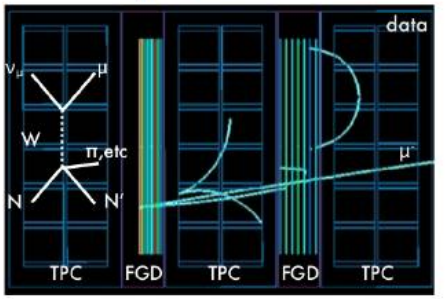




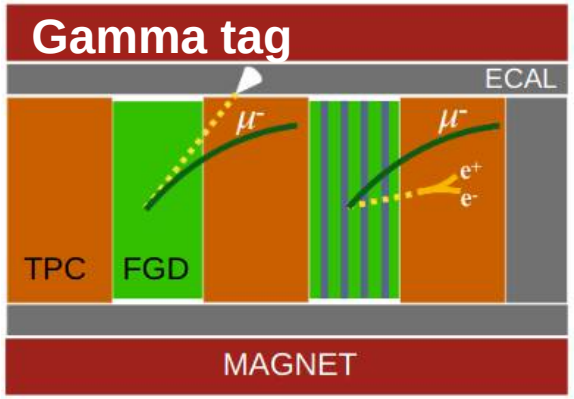




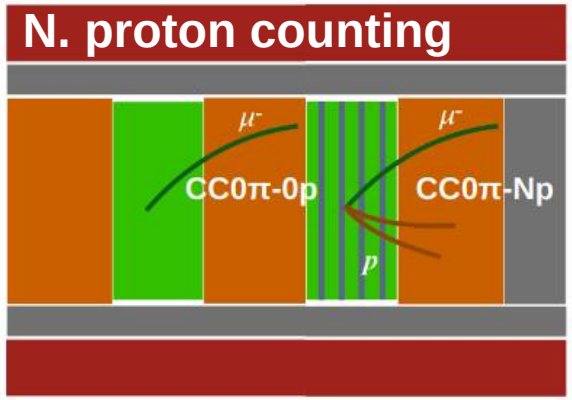




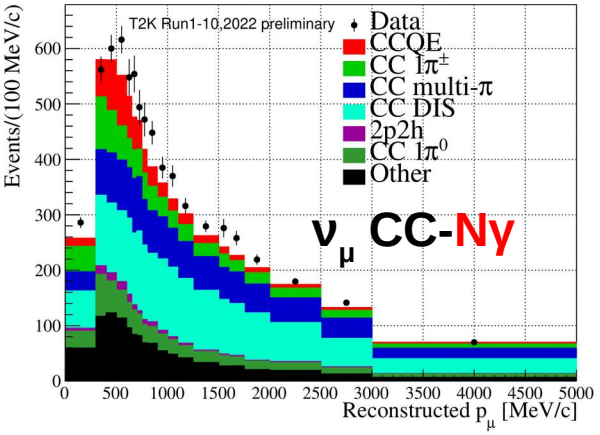
New(!) ν-mode samples ($\bar{\nu}$-mode unchanged)



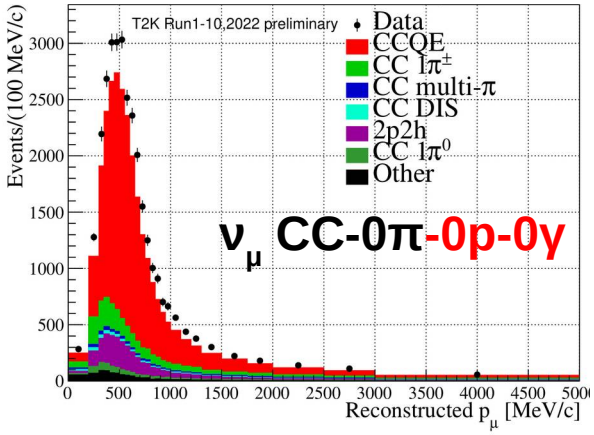
- Improves sample purities
- New (mostly DIS + multi-π) sample with FS π^0

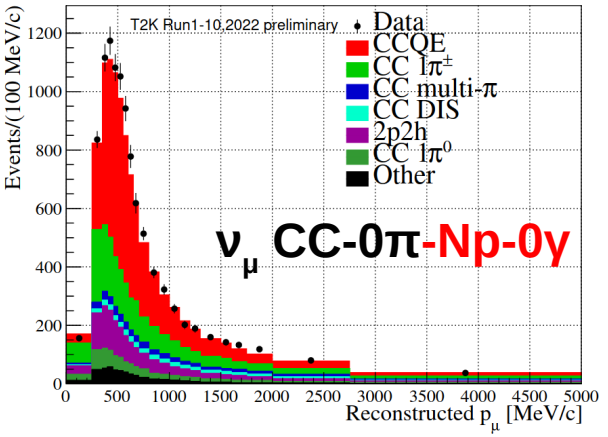


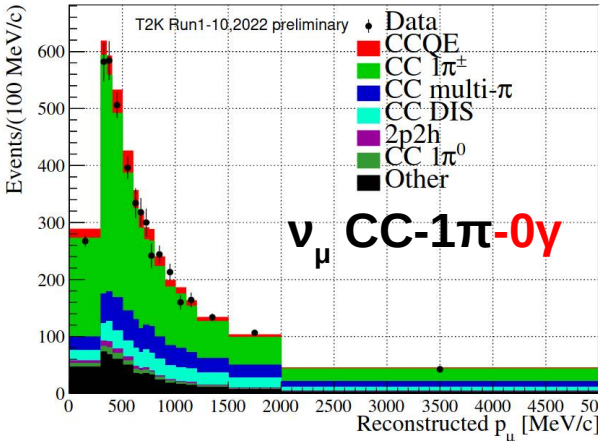
- Subdivide CC0π sample
- Constrain 2p2h + nuclear models

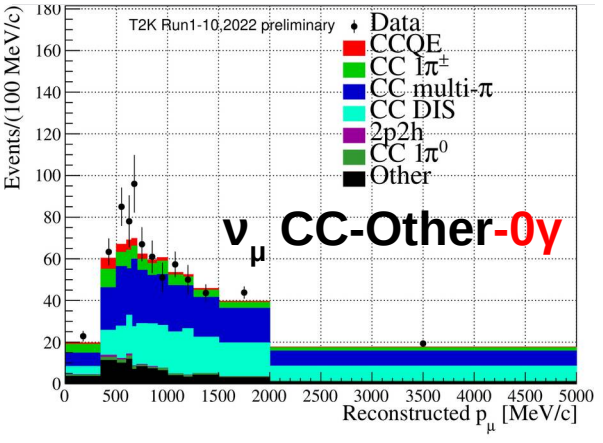


(FGD1 shown here)





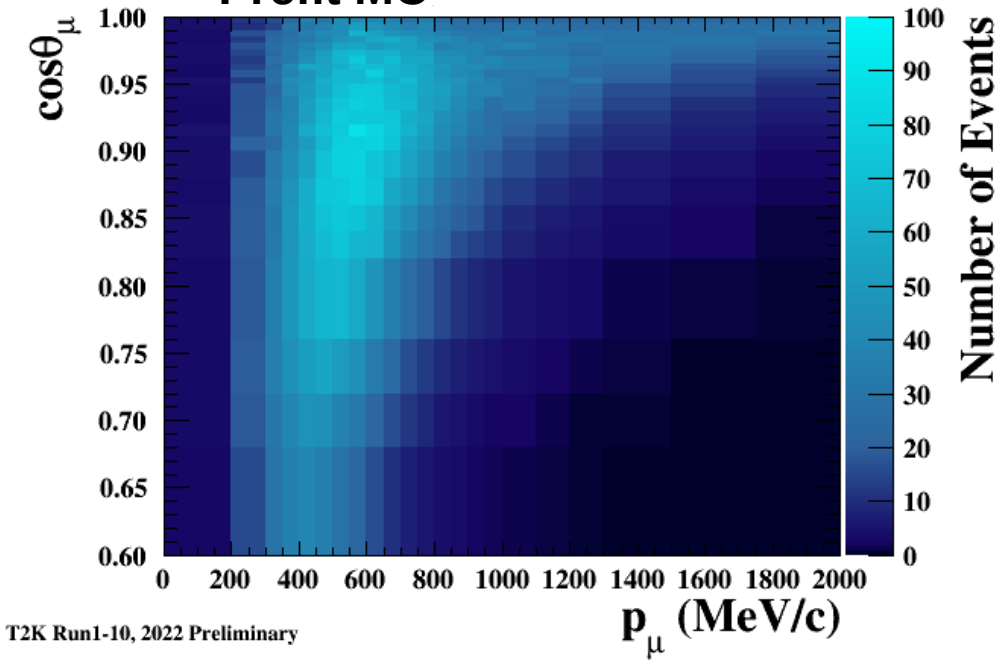




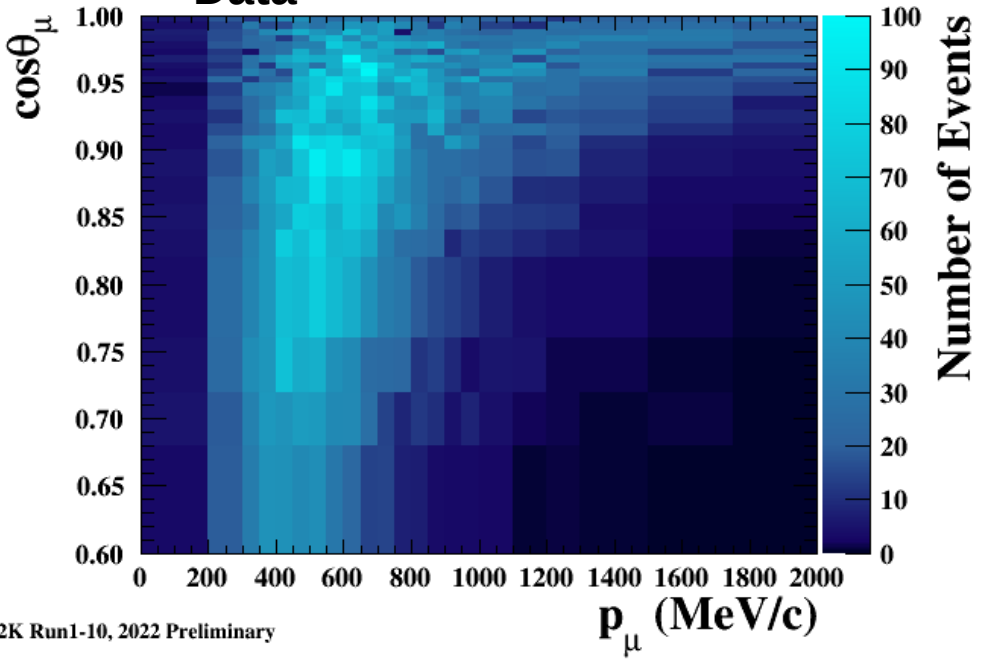
All samples in p_μ-cosθ_μ

Example: ν-mode FGD1 CC-0π-0p

Prefit MC



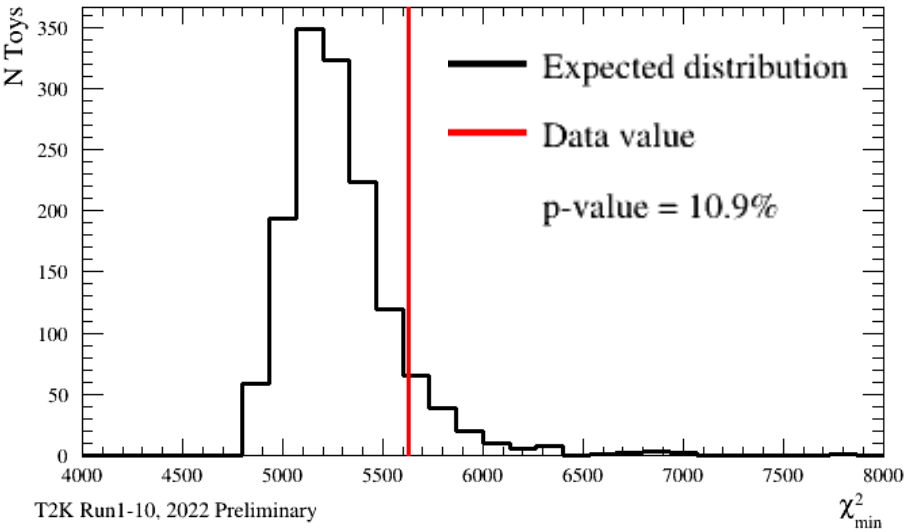
Data

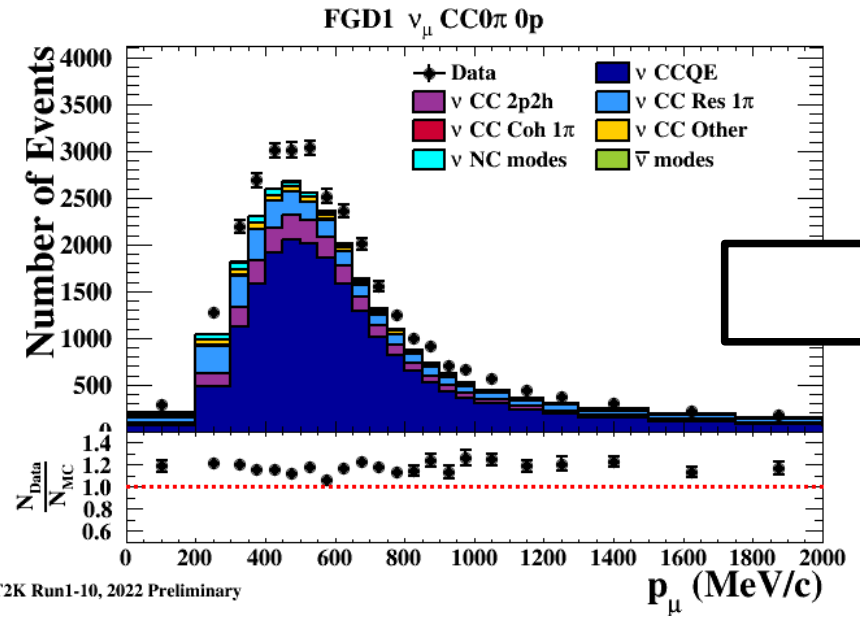


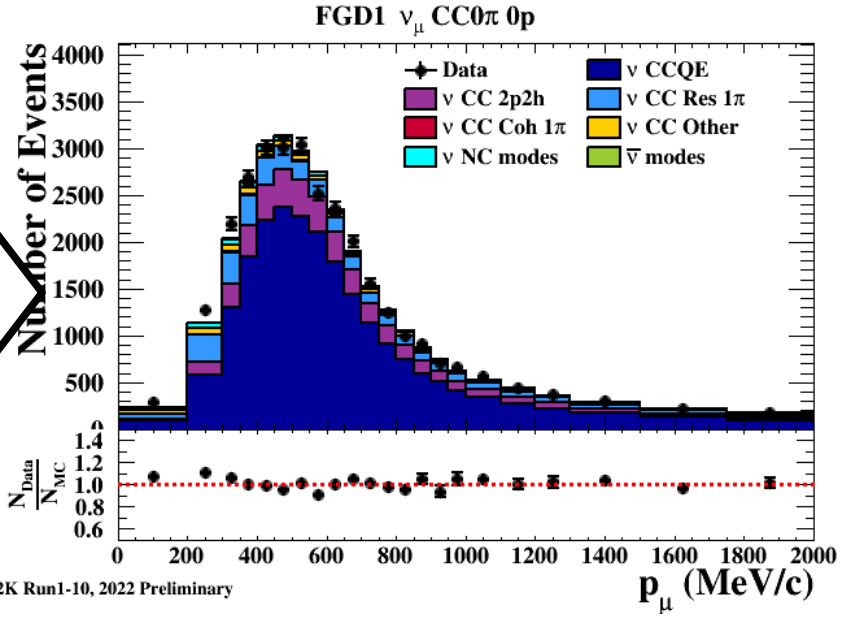
ND280 fit

- Extended binned LLH fit: 22 (p_μ-$\cos\theta_\mu$) ND samples + flux, XSEC and detector systematics
- Also, separate Bayesian approach with MaCh3 MCMC
- Various ND fit criteria before proceeding to FD fit (e.g., p > 0.05)

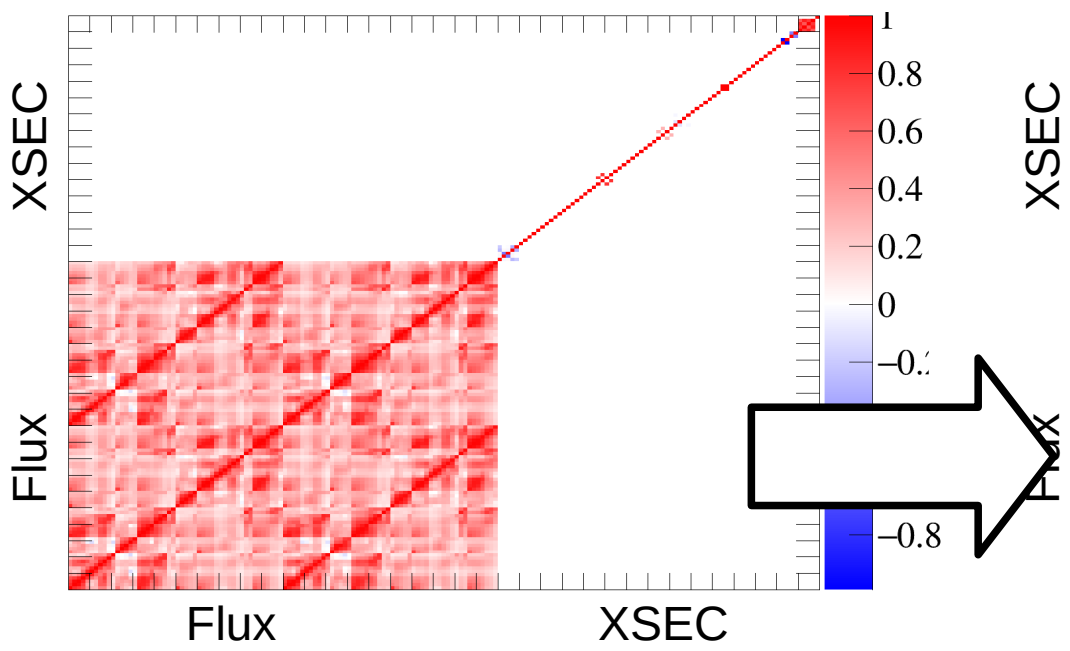
2000 syst+stat throws



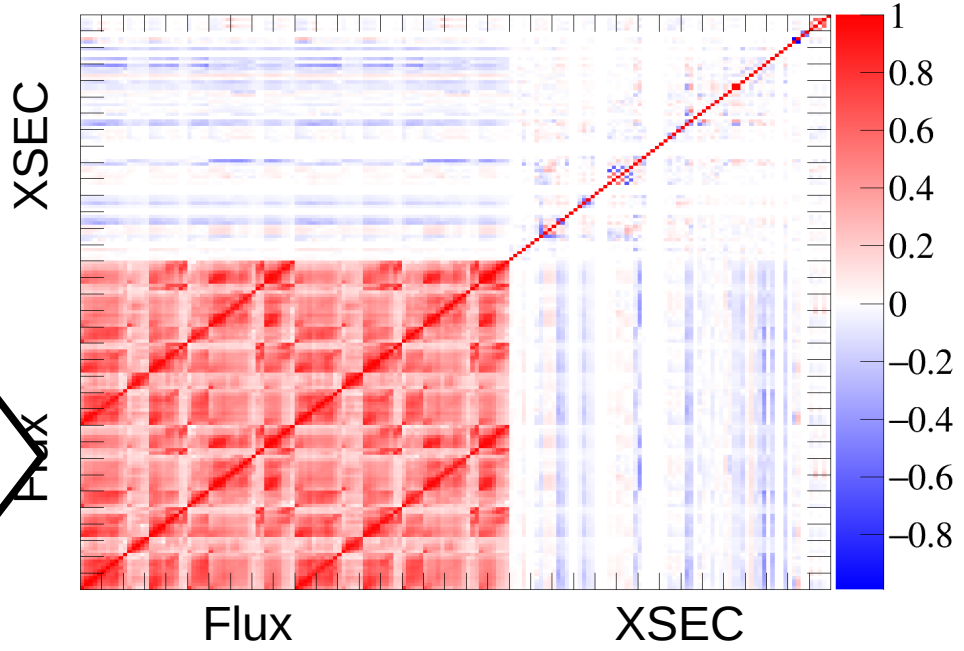




ND280 constraint



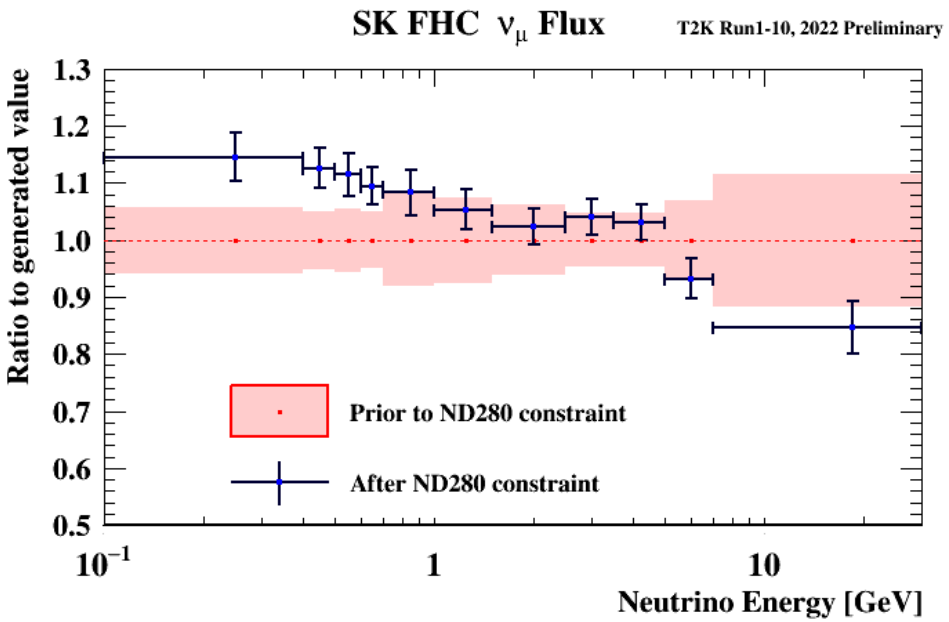
T2K Run1-10, 2022 Preliminary

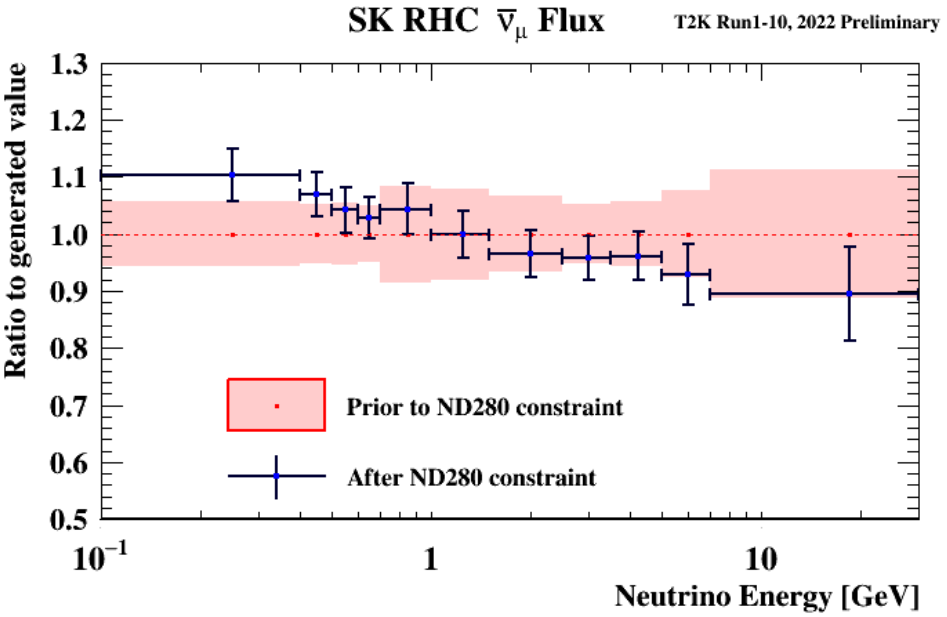


T2K Run1-10, 2022 Preliminary

- Central values and uncertainties of systematics change as data updates model assumptions
- Strong *rate* constraint introduces anticorrelation between flux and XSEC

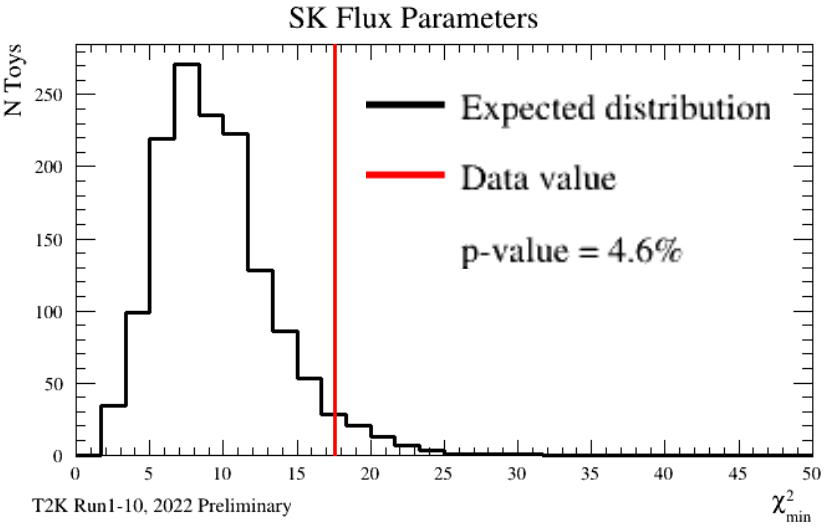
Flux constraint



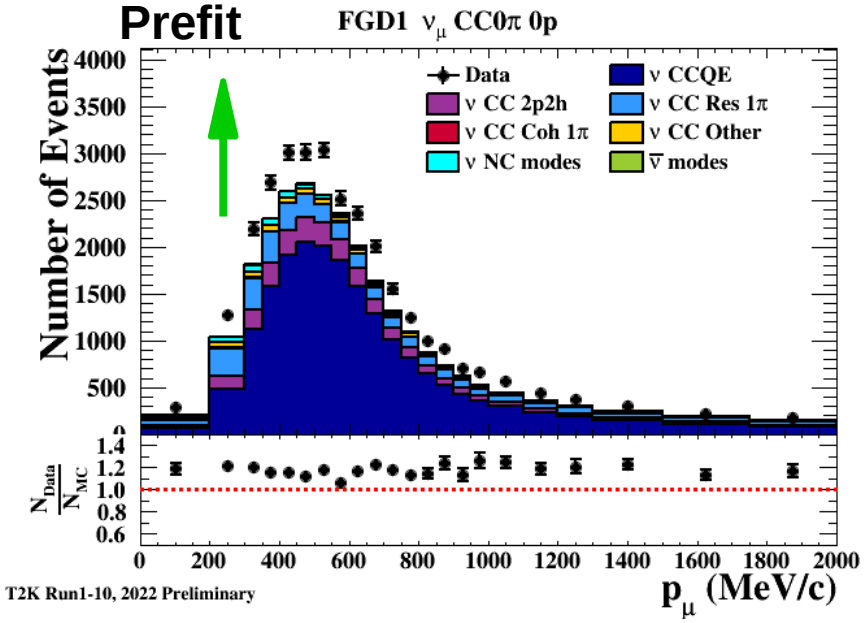


- Flux prediction at SK is updated using correlations with ND flux
- (Approximate) p-value* for flux is okay, despite parameters moving around

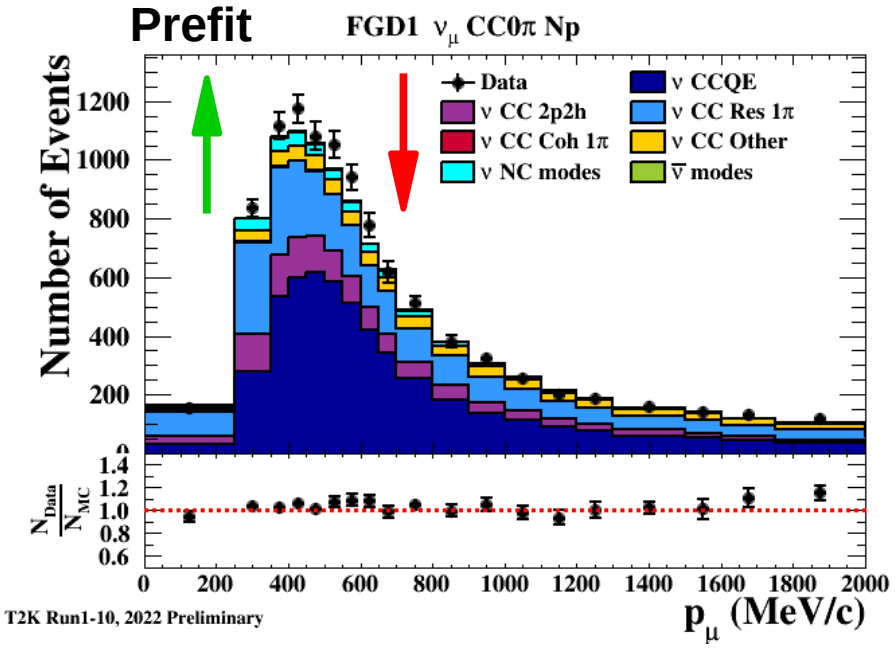
**Not a true p-value as correlations with other parameters are neglected*

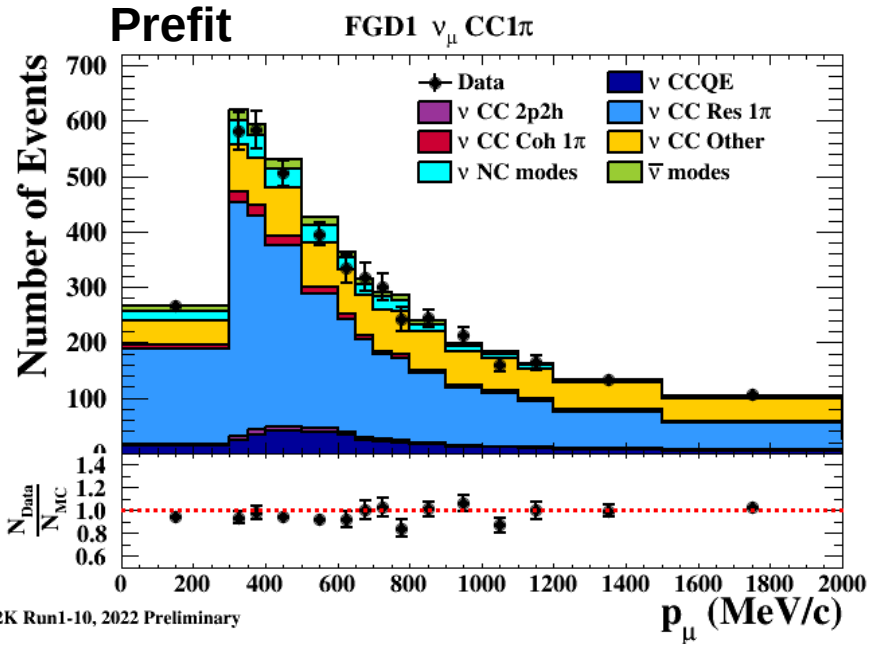


Example: impact on XSEC parameters



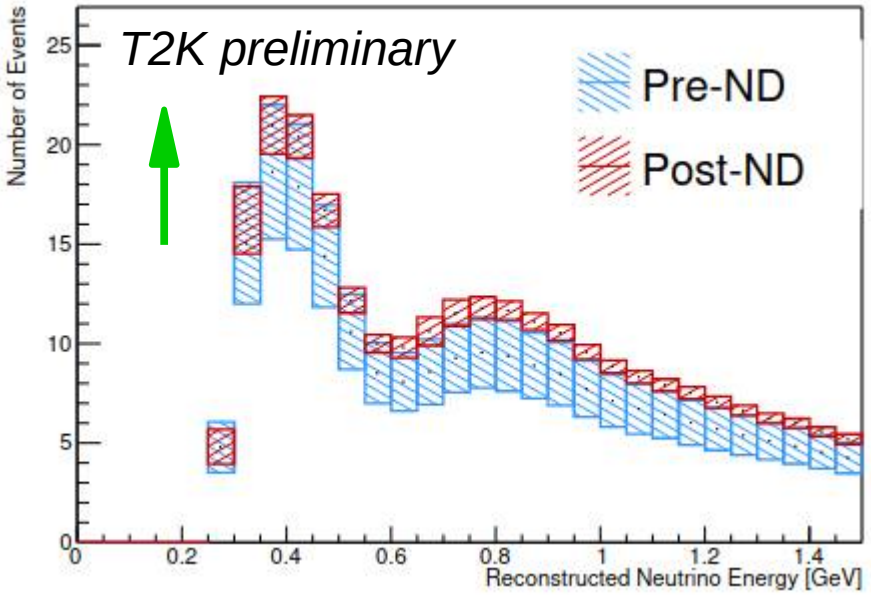
- Deficit in CC0π0p sample, no deficit in CC0πNp or CC1π
- **CCQE increased** to compensate, *rate increase in SK prediction!*
- **2p2h suppressed** to retain CC0πNp agreement



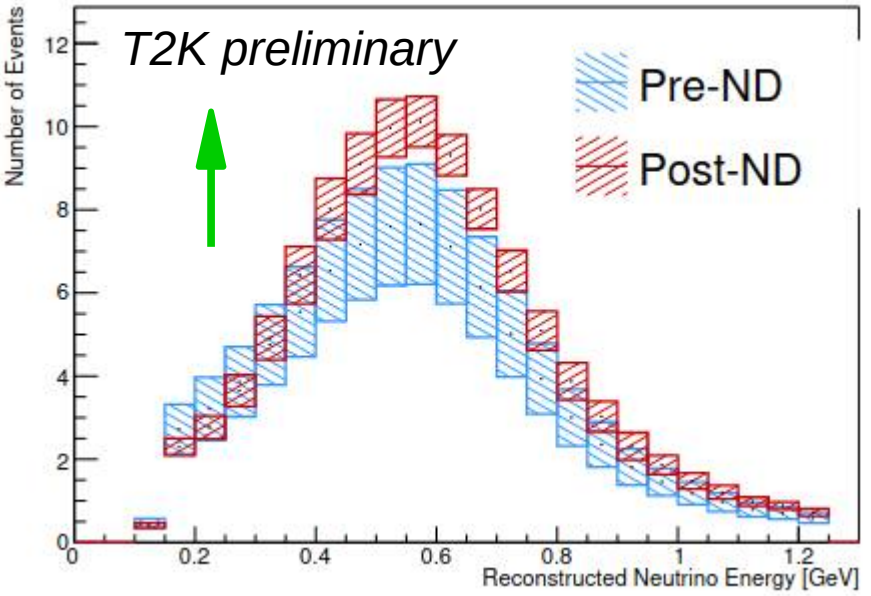


Impact on the SK prediction

ν-mode μ-like CC0π



ν-mode e-like CC0π



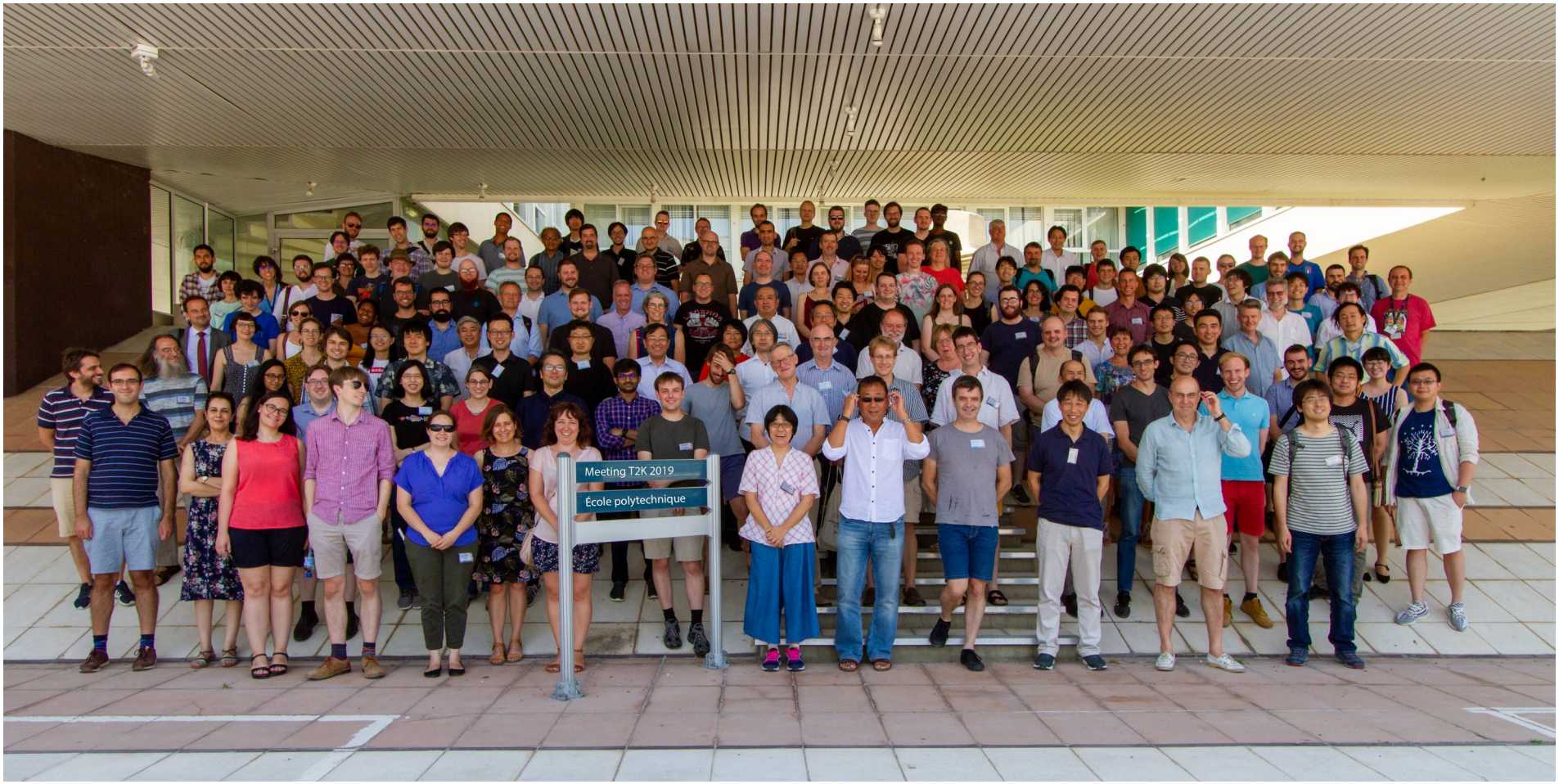
- SK prediction is updated by the ND-constrained model
- Uncertainty on flux+XSEC reduced to be less than the SK detector uncertainty
- Details of oscillation fit in K. Yasutome's talk tomorrow!

Summary

- T2K ND is crucial for achieving our oscillation physics results
- Continued efforts to refine the ND samples which are included in the analysis
- Tightly coupled development with cross-section model and in response to new SK samples
- New opportunities with T2K ND upgrade, see A. Eguchi's talk next!

T2K collaboration

~500 members, 76 institutes, 13 countries (+CERN)



Backup

Impact of BANFF fit at SK

Prefit

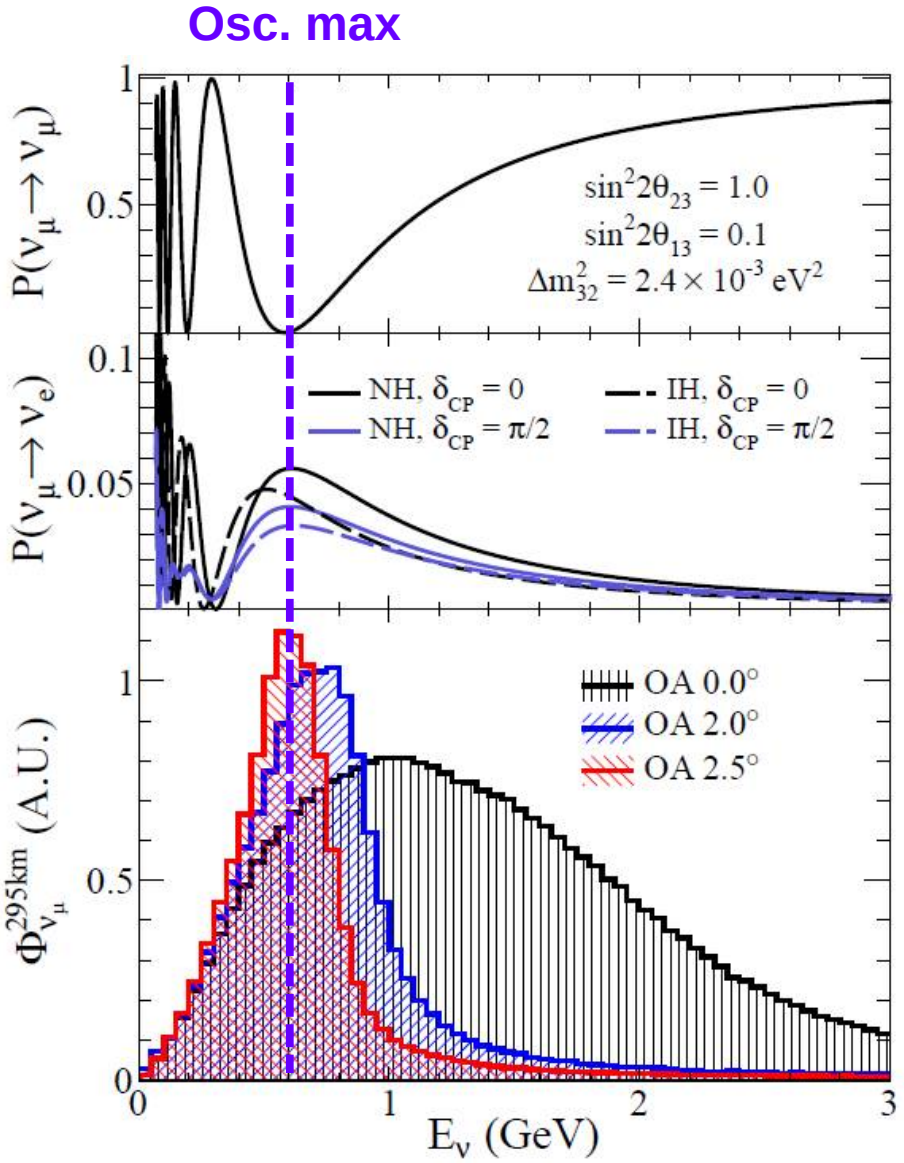
Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	5.0	4.6	5.2	4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6	16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0	3.1	3.9	13.6	1.3
Total All	16.7	14.6	12.5	17.3	14.4	20.9	11.6

Postfit

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9	5.2	5.8	14.3	4.5

Off-axis technique

- Two body decay → maximum transverse component to the neutrino momentum
- Moving off-axis reduces the neutrino flux peak, and width of the distribution
- 2.5º off-axis → ~0.6 GeV narrow flux peak



Context: long-baseline oscillation experiments

Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability

$$R(\vec{\mathbf{x}}) = \overbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times \underbrace{P(E_\nu; \nu_A \rightarrow \nu_B)}_{\text{Far}}$$

- Complex inference of **oscillation probability** from **event rate**
- Near detector constrains **flux** and **cross-section** systematic models
- But, uncertainties do not neatly cancel due to different fluxes + *different detectors*